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13. ABSTRACT (Maximum 200 words)  We have demonstrated that polymer optical fiber can be built into smart photomechanical devices that have the ability to sense strain and to make mechanical adjustments accordingly. The first bulk device demonstrated is an all-optical vibration stabilizer that is capable of keeping the position of a mirror fixed to within one part in $10^8$ . This device is unique in that no electronics are used: light powers the device; light acts as the sensing medium; light carries the information; the information is processed by light; and the light is used to move the material by photomechanical action. We have also demonstrated that such a device can be miniaturized to sub-millimeter dimensions and that all the functions of the bulk device can be simultaneously imparted to one physical part of the device. Such devices can be connected in series or parallel to make ultrasmart associations that can be built into smart composite materials. Our devices have been patented and the technology is being transferred to industry.				
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# Smart Opto Mechanic Polymer Devices

Final Report

Mark G. Kuzyk

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## 1 Statement of Problem

The purpose of the proposed research was to demonstrate the photomechanical effect (i.e. light induced length changes of a material) and to use this effect to build smart all-optical devices that can be miniaturized and incorporated into materials to make them mechanically and/or optically 'smart.' We exceeded all proposed milestones as described below.

## 2 Technical Summary

Under present ARO support, we have demonstrated that polymer optical fiber can be built into smart photomechanical devices that have the ability to sense strain and to make mechanical adjustments accordingly. We begin with a description of bulk devices that have been demonstrated in our laboratory then discuss a new design that we have applied to drastic miniaturization.[1, 2, 3]

### 2.1 Vibration Suppressor

Figure 1 shows a schematic diagram of an experiment that demonstrates the smart response of an optical fiber. In particular, this is an example of an all-optical circuit that probes the position of a mirror and sends the light-encoded information to the optical fiber, which actively readjusts the position of the mirror to keep it fixed. Aside from acting as an efficient vibration compensator, this device also acts as a mechanical actuator and digital positioner. In all three operational modes, light is used for sensing, information transmission, and mechanical actuating. Such devices are thus fast, lightweight, immune from electromagnetic

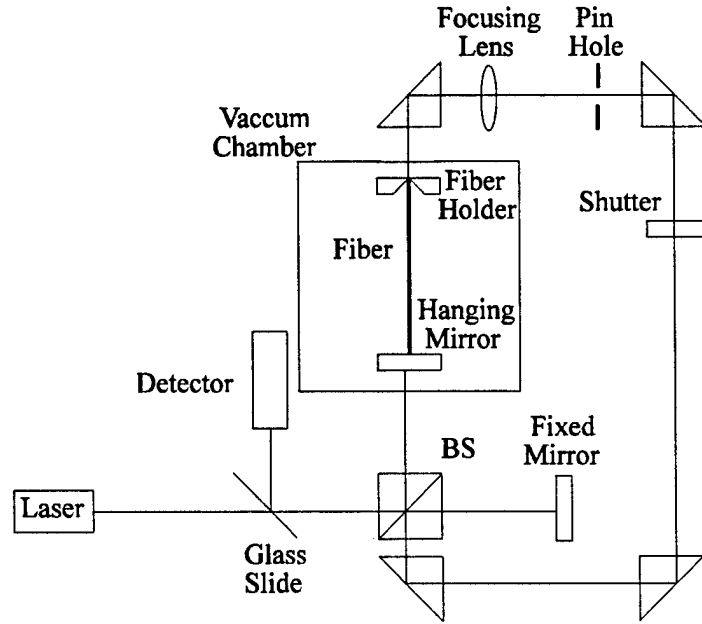


Figure 1: Schematic diagram of a smart fiber that acts as a vibration suppressor, continuous positioner, and digital positioner.

interference, secure from eavesdropping devices, and safe in explosive environments. Furthermore, they are compatible with the growing number of high-tech optical devices whose operational characteristics greatly exceed those of their electronic counterparts.

The mechanism of active stabilization in such a device can be understood as follows. A laser beam is launched into a beam splitter (BS) that separates the light into two equal parts. One of these beams is reflected from a mirror that is attached to the hanging fiber while the second beam reflects from a fixed mirror. The two beams then recombine at the same beam splitter and are directed to a prism. Because the light beams are waves, they interfere with each other when combined by the beam splitter: the intensity leaving the interferometer is maximum when the two beam paths are equal and is minimum when the path difference is a half integer multiple of the light wavelength. The output of the interferometer is thus a sinusoidal function of the path difference (i.e. fiber length) with a period that equals half the wavelength of the light. Figure 2 shows one oscillation of this function.

The light leaving the interferometer is sent to the hanging polymer optical fiber. Through photothermal heating, the light deposits energy to the fiber, which results in thermal expansion. The fiber elongates until it reaches an equilibrium state in which the light energy absorbed is equal to the energy leaving the fiber through Newton cooling. If the light intensity drops, the fiber cools and the length decreases. The line in Figure 2 represents the fiber's length dependence on the light intensity inside the fiber. The slope of this line is determined by balancing the cooling rate and the rate at which energy is deposited into the fiber and is found to be inversely proportional to the light intensity in the fiber. The stable point of the system is determined by the intersection of the line and sinusoidal curve. Note that for a polymer fiber of positive thermal expansion coefficient, the length  $L_0$  is stable while  $L'_0$  is not stable. For a negative coefficient of thermal expansion, the two are reversed, that is, the point given by  $L'_0$  is stable and  $L_0$  is not.

The stabilization process can be analyzed by considering the response of the system to

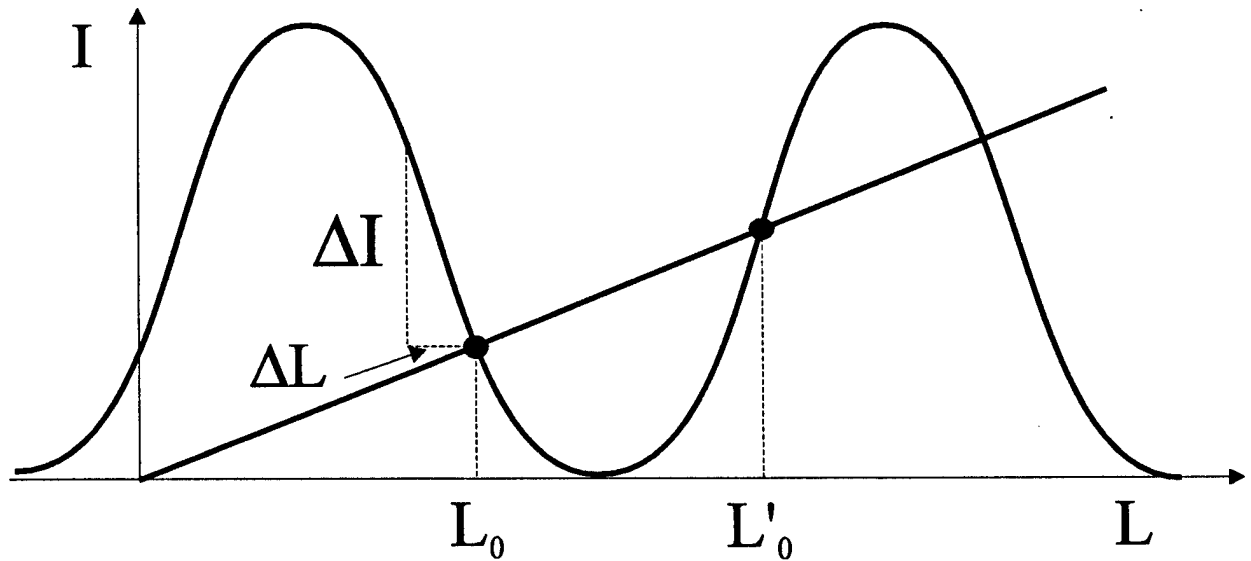


Figure 2: A plot of the interferometer output intensity (normalized to unity at maximum intensity) as a function of length (sinusoidal curve) and the fiber length as a function of light intensity in the fiber.

a mechanical impulse. If the fiber length is decreased by an amount  $\Delta L$  by an external impulse, the light intensity leaving the interferometer will increase by an amount  $\Delta I$ . The fiber will then expand due to photothermal heating and compensate for the impulse. Slow temperature drifts in the environment will not effect stabilization. In fact, changes in fiber temperature will be actively compensated by optical feedback. As an example, if a decrease in ambient temperature results in fiber contraction, the intensity leaving the interferometer will increase, thus heating the fiber and bringing it back to its original temperature and length. The temperature stabilizing effect will occur as long as the ambient temperature change is not large enough to increase the fiber length by more than the light wavelength. It is clear that the temperature stabilization process is similar to length stabilization.

Figure 3 shows the output of the interferometer as a function of time. The shutter is closed between 0 and 270 seconds. Without feedback the fiber length changes with time, as evidenced by the intensity drift. Such drift is common in interferometers. When the shutter is opened to allow for feedback, the fiber length stabilizes. The amplitude of the ripples in the intensity is a measure of the degree of stabilization. We find that the 30cm fiber length can be maintained to within 2nm. This corresponds to an accuracy in fiber length to within one part in  $10^8$ . Note that the fiber length changes abruptly to a new value at about 310 seconds. This behavior is explained below.

## 2.2 Digital Positioner

Figure 2 shows one oscillation of the sinusoidal dependence of the interferometer output as a function of fiber length. Figure 4 shows an extension of this plot over several oscillations. It is clear that there are a series of stable equilibria at the intersection of the sinusoidal curve with the straight line as labeled by the dark squares. Because the slope of the line is inversely proportional to the intensity of the laser source, the number of equilibrium points increases with increased laser power. The jump in Figure 3 from  $n = 1$  to  $n = 2$  arises from the system hopping between two equilibrium points.

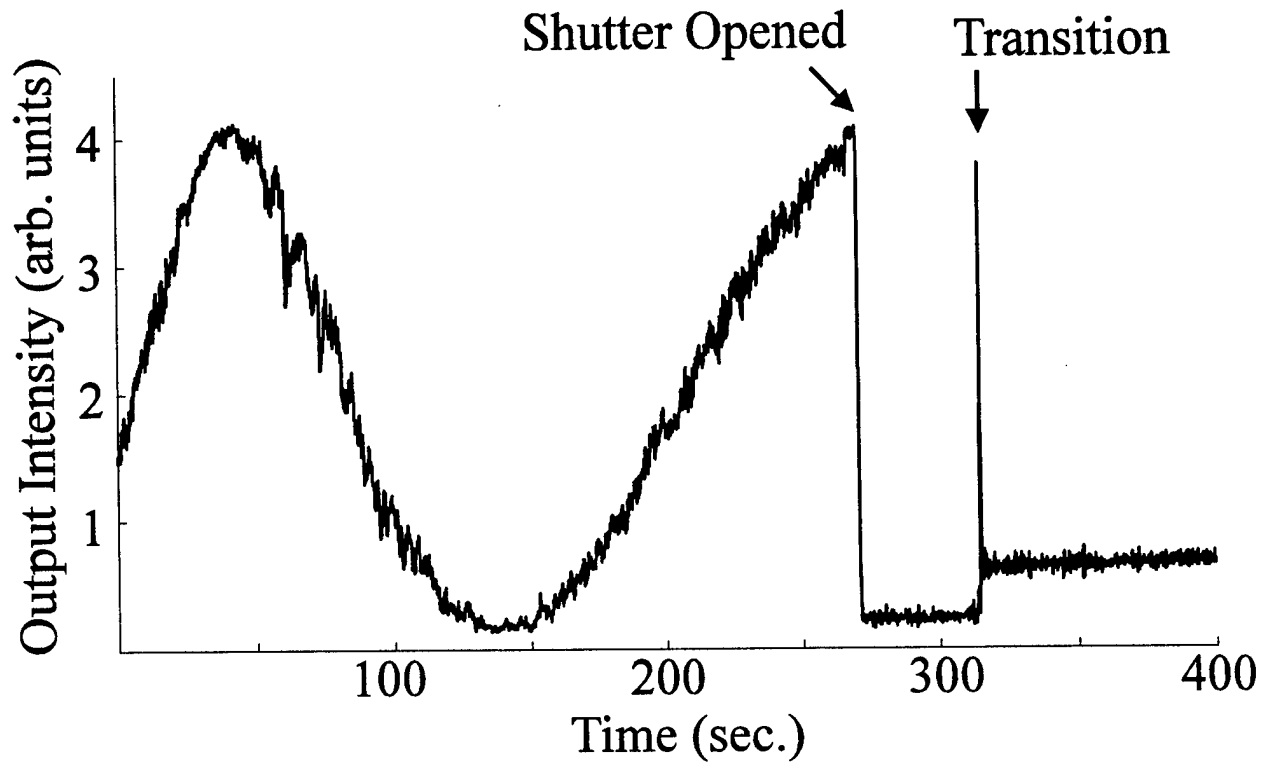


Figure 3: Light intensity output from the interferometer as a function of time. Feedback is turned on when the shutter is open.

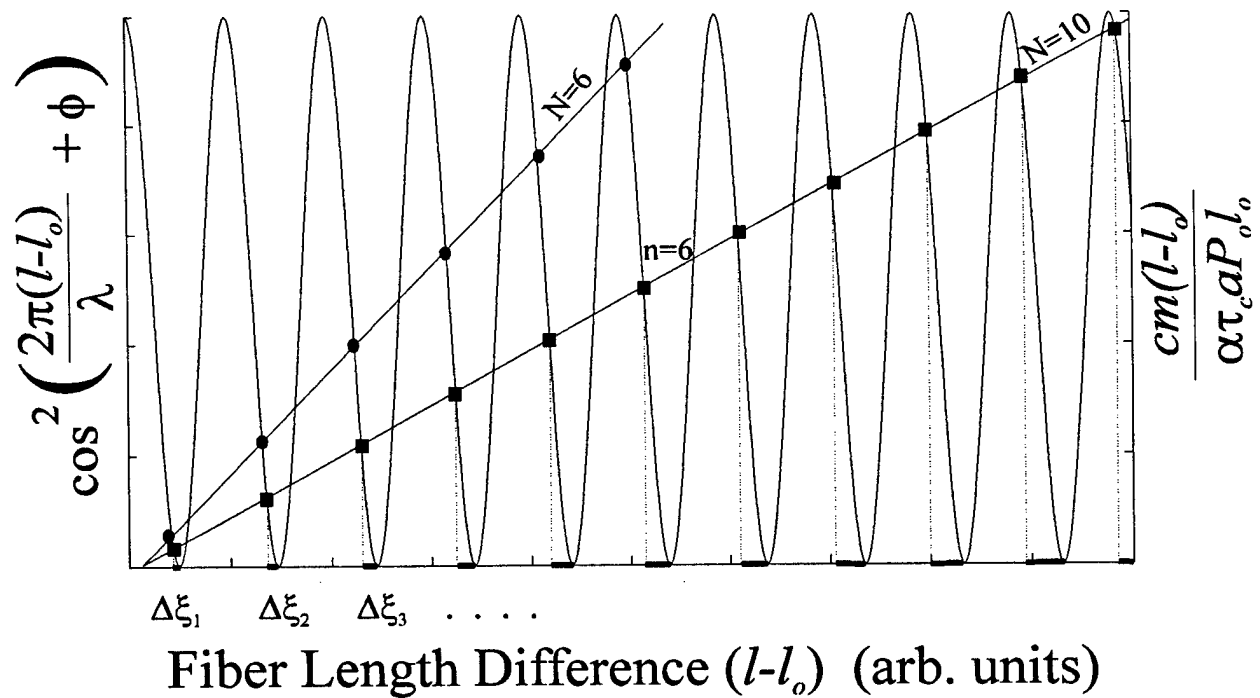


Figure 4: A plot of the interferometer output intensity (normalized to unity at maximum intensity) as a function of length (sinusoidal curve) and the fiber length as a function of light intensity in the fiber over a range of lengths that corresponds to many oscillations of the sinusoidal function.

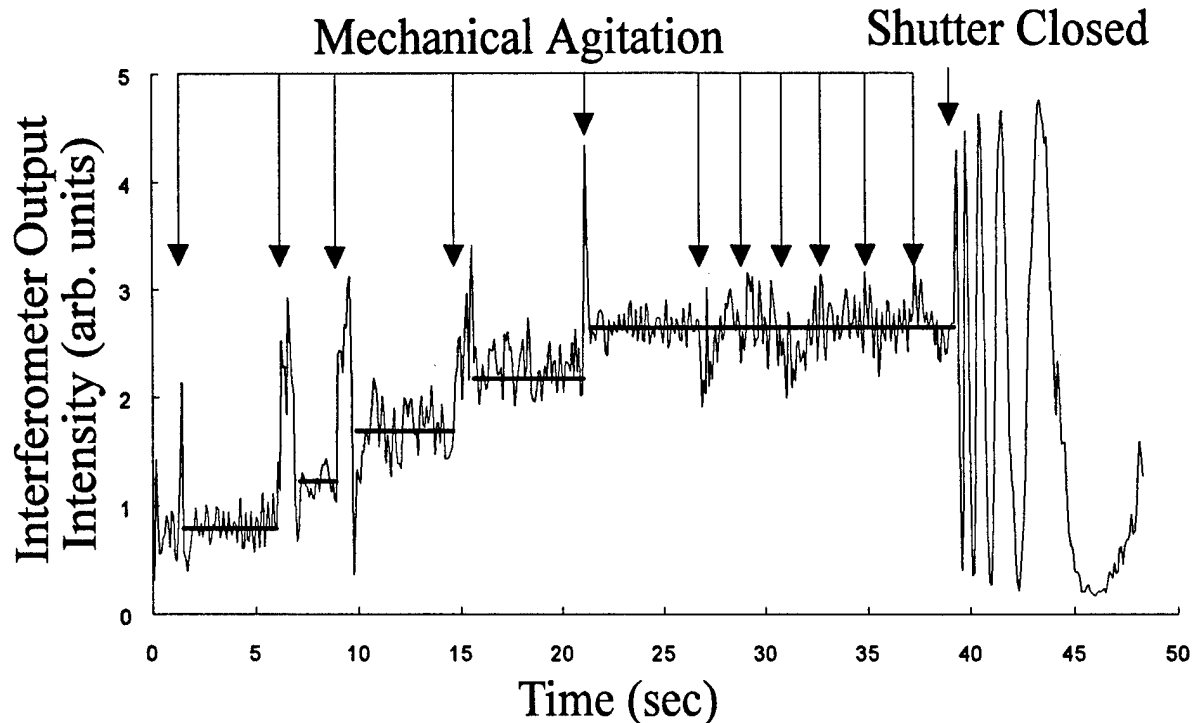


Figure 5: Light intensity as a function of time for a fiber under mechanical agitation. Arrows show times at which the system is agitated.

The relative instability of the  $n = 1$  point can be understood as follows. The range of lengths over which the fiber length will be stabilized spans the region between the stable point and the next minimum of the sinusoidal function. These stable regions are highlighted by a dark line on the length axis of Figure 4. The range of stability increases for successively higher  $n$ . When the region of stability is small, any small changes in the fiber length that exceed the highlighted region will result in the fiber jumping to the next stable point. Another factor affecting relative stability is the strength of stabilization. This strength should be maximum when a small change in fiber length results in a large change in intensity in the fiber. This occurs at the point of maximum slope on the sinusoidal curve. The point  $n = 1$  is clearly the least stable solution owing to the fact that the slope is small and the stable region is small. For a system with  $N$  stable points, the point  $n \approx N/2$  should be the most stable.

To verify that  $N/2$  is the most stable point, we must develop an experimental method for forcing the system into any arbitrary state. Once a particular state is reached, we can test the strength of stabilization by testing the system's resistance to vibration. The simplest method for reaching a given length state is to apply mechanical agitation of sufficient strength to successively kick the system through its equilibrium states. Figure 5 shows the results of an experiment in which mechanical agitation is used to kick the system through a series of stable lengths.

The multiple points of stability are clear. After the system reaches the state  $n = 6$ , we have found that it is not possible to mechanically shock the system with enough force to move it to the next higher state. When feedback is turned off, the fiber relaxes and traces out 6 oscillations, as expected for  $n = 6$ . Given that the interferometer intensity at  $n = 6$  is about half of the maximum possible intensity,  $n = N/2$  as predicted.

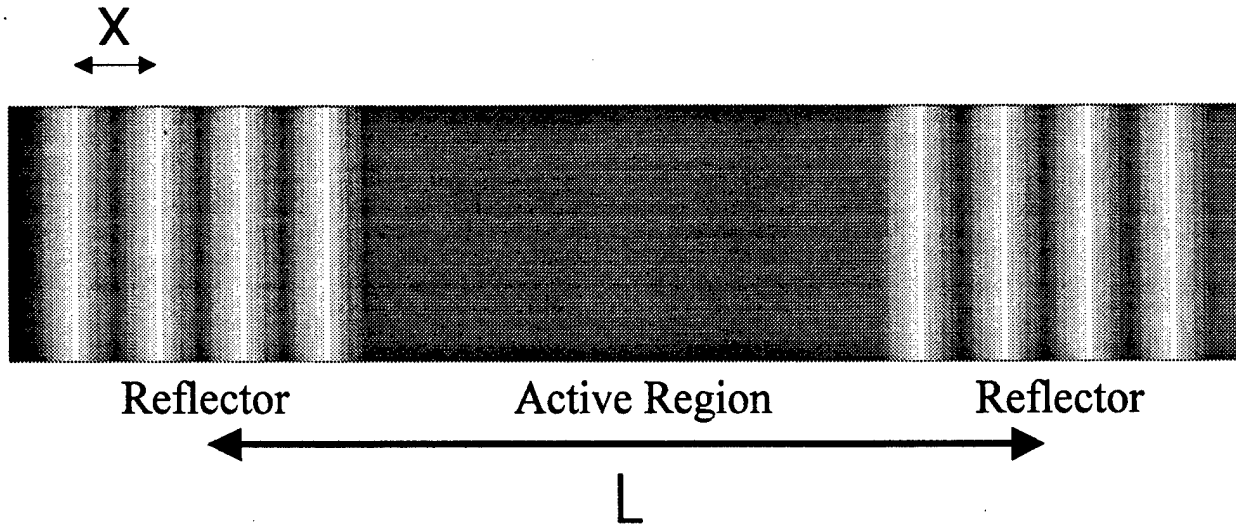


Figure 6: A miniaturized fiber stabilizer/positioner using an index grating reflector.

The length jumps in this experiment are on the order of 600nm and each point is stabilized to within about 2nm. For a system with a large number of equilibrium points, this device would act as a stabilized digital actuator.

### 2.3 Continuous Positioner

When the laser intensity is varied, the slope of the line in Figure 4 changes. The fiber length is then given by the intersection of the line and curve; a continuous change in slope of the line will result in a continuous change in the fiber length. The length can thus be varied over a corresponding intensity range that spans from a peak in the sinusoidal function to the next minimum, that is, a quarter of a wavelength of the light.

The device, then, is a stabilizer that reduces vibrations to less than 2nm, acts as a digital positioner in 600nm steps, and can be continuously tuned over a 150nm range within each step by varying the input laser intensity.

### 2.4 Miniaturized Smart Fiber Devices

Photomechanical devices must be miniaturized if they are to be built into smart materials. Miniaturization is particularly important in applications that require large arrays or interconnected devices. We have designed such a device using a fiber Fabry Perot interferometer, and its operational characteristics should match or exceed the demonstration device (Figure 1). Figure 6 shows a possible device geometry that consists of a fiber waveguide that incorporates two reflectors inside the fiber that are separated by a distance  $L$ . The refractive index grating reflector of periodicity  $x$  operates on the principle that a spatial refractive index grating whose period is half the light wavelength will reflect a large portion of the incident light provided that there are a sufficient number of layers within the grating. Given its size and function, we call the Fabry-Perot interferometer device a mesoscale-photomechanical-unit (MPU). (Note that a glass fiber with a single grating has been demonstrated to act as a pressure sensor, that is, the reflectivity from the grating depends on strain.[4])



Light is launched into one end of the fiber structure. The light then bounces back and forth between the reflectors. A portion of this light is transmitted to the output side of the fiber and the rest is kicked back towards the incident laser source. Because all beams are referenced to the MPU, the beam that leaves the device along its original direction is called the transmitted beam while the backward-propagating beam is called the reflected beam.

This simple device incorporates an internal feedback mechanism: the two reflectors define an interferometer in which the counter propagating light beams bouncing between the reflectors are analogous to the two arms of the interferometer. The light intensity between the reflectors is a periodic function of their separation and the fiber length depends on the intensity of light between the reflectors.

While the light intensity inside the fiber is a periodic function of the fiber length, it is not sinusoidal as it is in the Michaelson interferometer: the peaks are narrower and the minima are flatter. The width of the intensity peak of a Fabry Perot interferometer is quantified by a parameter called the finesse. The finesse is related to the reflectivity of the surfaces and is a measure of the average number of times that the light bounces back and forth between the reflectors before leaving the interferometer. For a static light input, the reflected light, transmitted light, and the light between the mirrors will be constant over time. The light intensity inside the interferometer, however, can greatly exceed the incident intensity. The higher the finesse, the sharper the peaks and the greater is the light intensity inside the device. The points of stability are again given by the intersection of the periodic curve with the straight line which represents the equilibrium between photothermal heating and Newton cooling. Of significance to vibration suppression is the fact that the larger slopes and greater intensities of the sharper peaks result in a much larger stabilization force than for the Michaelson interferometer.

We have succeeded in making a polymer fiber MPU of 2cm length and  $100\mu\text{m}$  diameter. The fiber is doped with a disperse red azo dye to increase the degree of photothermal heating. Even with its shorter length, the dye-doped MPU's operational characteristics are similar to the 30cm fiber. For purposes of MPU demonstration, we have used a retroreflector geometry instead of the more-difficult-to-fabricate refractive index grating reflector. Figure 7a shows a schematic representation of the fiber and retroreflector end. The principle behind the retroreflector geometry is total internal reflection. Those rays that are incident on the fiber end at an angle that exceeds the critical angle (about  $45^\circ$  in PMMA polymer) are reflected. If the fiber end is cut to an angle that is close to  $90^\circ$ , rays traveling down the fiber axis will be reflected twice resulting in a net back reflection. Other rays that meet the fiber end below the critical angle will be transmitted. The fiber end thus acts as a partial reflector. As shown in Figure 7b, an impurity or defect in the fiber can act as an additional partial reflector thus adding two more MPUs to the fiber.

In order to evaluate the photomechanical properties of a fiber MPU, we have measured the output intensity of the fiber as a function of the input intensity. An output intensity that is a multivalued function of the input intensity is a sign of multistability.[5, 6] In such transmission experiments, there are two possible sources of multistability: length and refractive index mechanisms. Photothermal heating usually results in both a refractive index change and length change.[7] The relative importance between the length change mechanism and refractive index change mechanism can be estimated from the thermal expansion coefficient and the thermal refractive coefficient.[8] For PMMA polymer, the refractive mechanisms is about twice as large as the length change mechanism. Any observation of multistability is

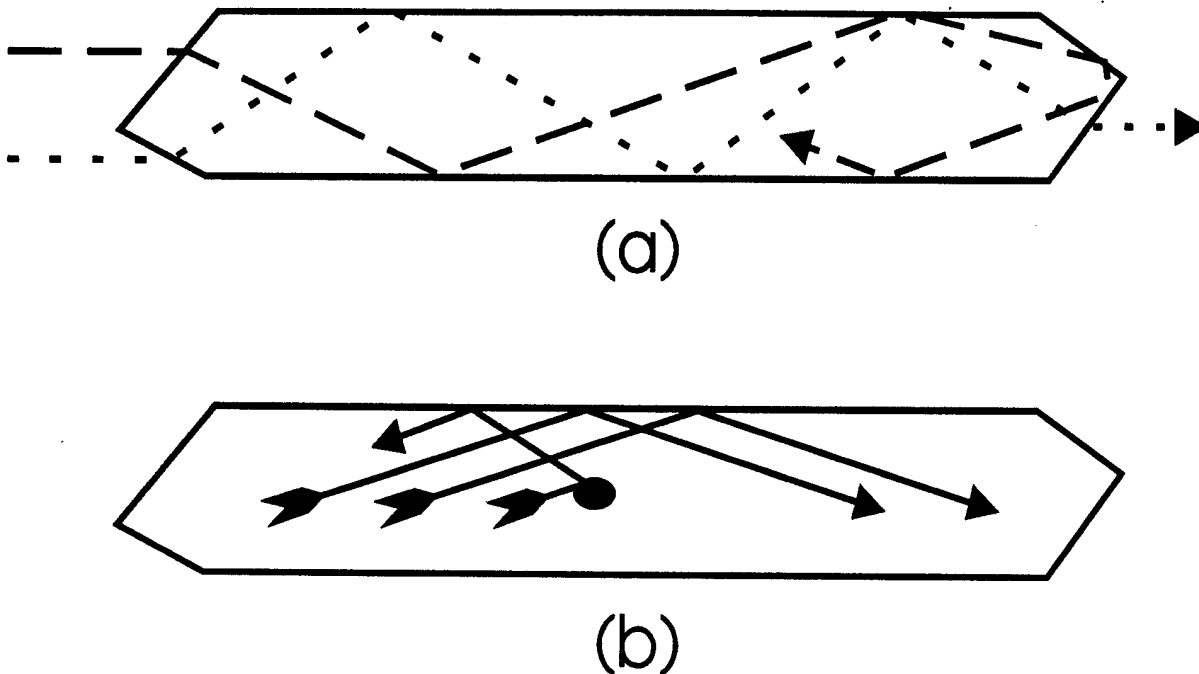


Figure 7: Schematic representation of a polymer fiber waveguide Fabry-Perot cavity defined by a pair of retroreflectors. a) Dashed ray is reflected by total internal reflection and dotted ray is transmitted. b) An impurity or defect can result in additional reflectors thus effectively adding another Fabry-Perot cavity.

thus strongly suggestive that both mechanisms are present.

Figure 8a shows the output versus input intensity for an MPU that is about 2cm in length and  $100\mu\text{m}$  in diameter. Figure 8b shows the output intensity as the input intensity is ramped up and Figure 8c shows the output intensity when the input intensity is ramped down. Figure 8a is thus a superposition of Figure 8b and 8c.

There are several interesting features in the data. First, it is clear that the system is multistable. We observe at least four stable branches. Second, there are certain regions of chaotic behavior. This is typical of a feedback system.[9] Based on these observations, we believe that this is an operational MPU. Furthermore, based on numerical simulations, we believe that the MPU behaves as two coupled Fabry-Perot cavities.[10] An impurity in the MPU, as depicted in Figure 7b, could lead to such behavior because the impurity would act as an additional reflector. As explained in the following section, the first item of proposed research is to evaluate a single MPU to understand its mechanical response.

## 2.5 Fast Photomechanical Effects

The photothermal mechanism used in the above devices has a 1ms-100ms response time that depends on the size of the device. We have also observed a fast photomechanical response in a polymer optical fiber when it is pumped with a high power optical pulse.[11] In these pump-probe experiments, a mirror is suspended from a vertical fiber inside a vacuum chamber (similar to Figure 1), and pump-pulse-induced changes in the fiber length are monitored with a separate probe pulse that measures the position of the mirror. By delaying the probe pulse relative to the pump, the temporal dependence of the length change can be determined.

The time-dependence of the length change suggests that two mechanisms are responsible.

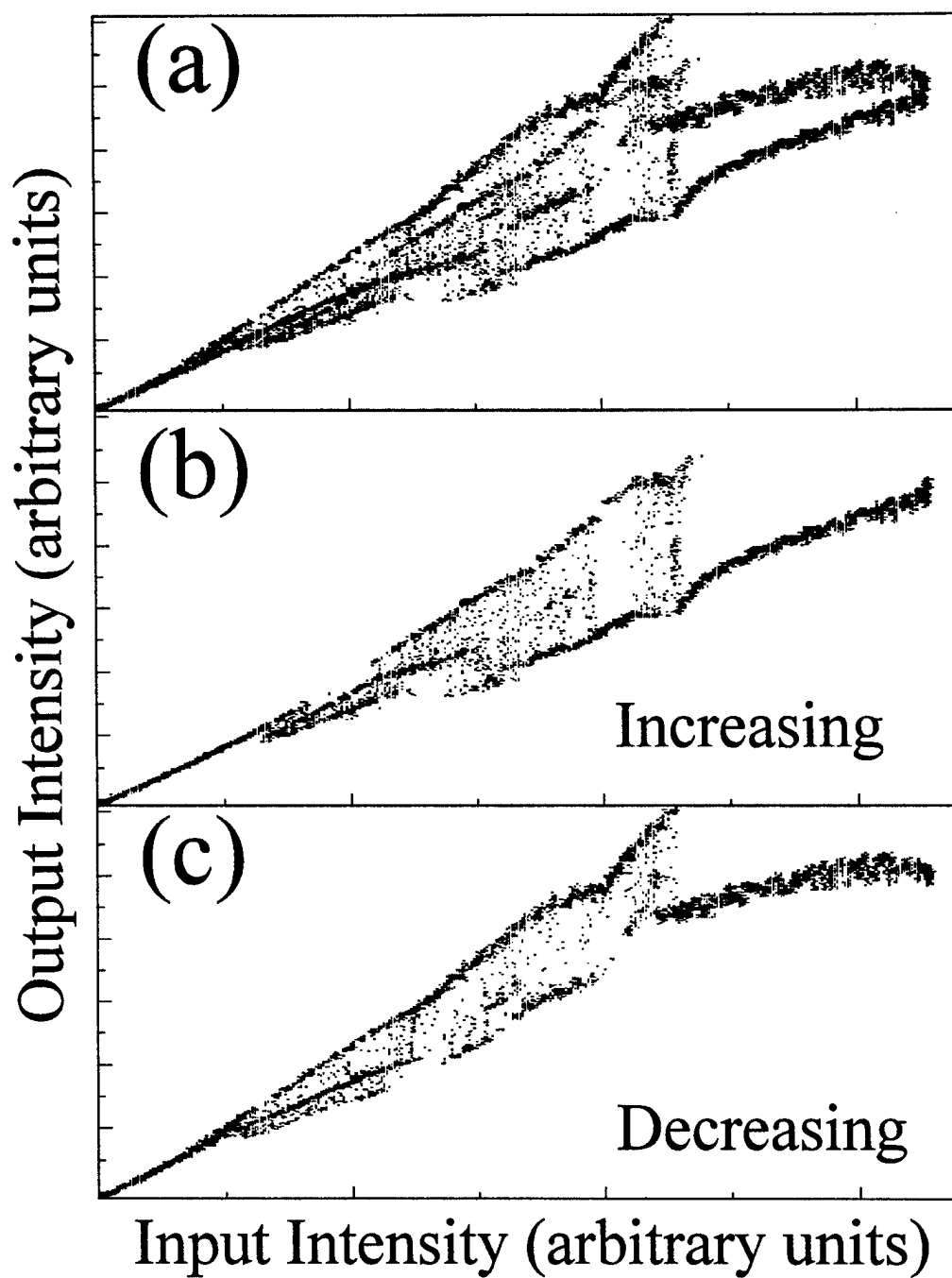


Figure 8: Output versus input at a ramp rate of 0.01425mW/s for a) one ramping cycle, b) for ramp-up, and c) ramp-down.

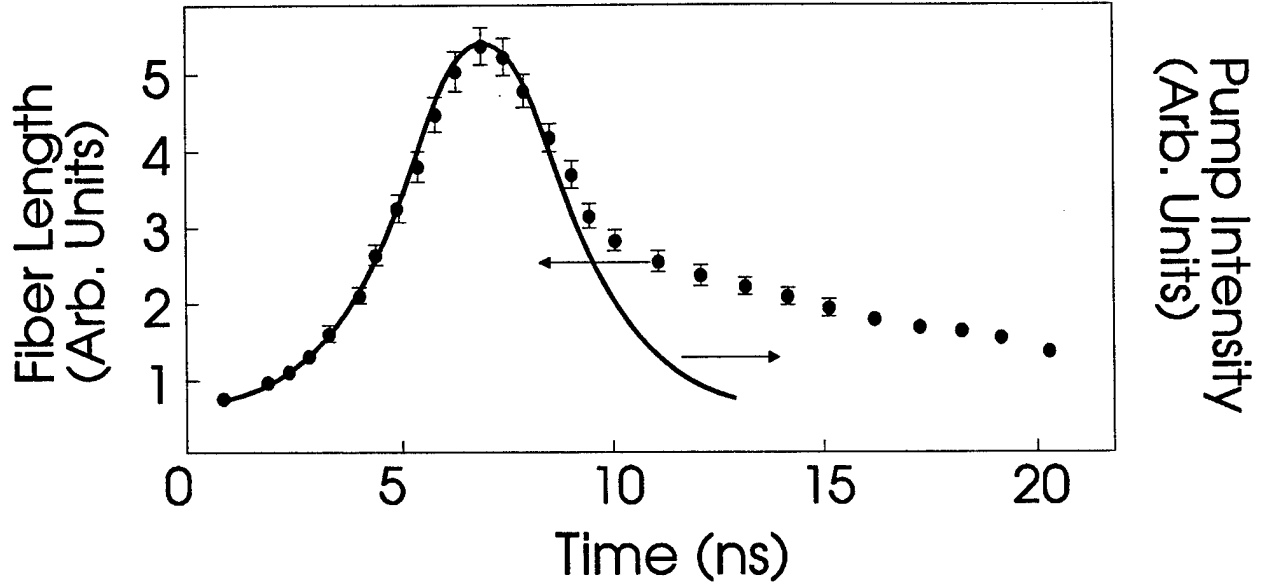


Figure 9: Fiber length (points with error bars) and intensity (smooth curve) as a function of time.

and the pump intensity as a function of time (smooth curve). The time-dependence of the length change suggests that two mechanisms are responsible. Over the first 3ns as the pump pulse turns on, the length change is observed to follow the pump intensity. After the pump pulse turns off, the length change relaxes with a time constant of about 12ns. Because the time resolution of our experiment is about 0.5ns, the upper limit of the fast mechanism is 0.5ns. We attribute the fast response to electrostriction.

Electrostriction is the process by which light squeezes a material and can be understood as follows. When a beam of light propagates inside a waveguide, its electric field changes most rapidly in the region near its surface resulting in a large electric field gradient at the surface. The field gradient results in a force that is perpendicular to the surface and points toward the waveguide. In an optical fiber, the force acts radially inward, squeezing the fiber surface around its waist and results in an hour-glass indentation where the light is the brightest, which in turn leads to an elongation of the fiber along its axis.

As a pulse of light travels down a fiber, its peak intensity coincides with the minimum fiber diameter at the hour-glass indentation around the fiber waist and extends along the fiber axis along the longitudinal length of the pulse. As the light pulse travels down the fiber, the hour glass travels with the light as a driven mechanical wave.

We have modeled the electrostrictive mechanism under the assumption that the normal force acts only at the surface, and, that the field gradient is given by the rate at which the evanescent electric field decays as a function of the distance from the fiber surface. For typical pump pulses of 6ns duration and about 5mJ of energy, our model predicts a 20nm length change for a polymer fiber of 200 $\mu$ m diameter. Given the crudeness of our model, it agrees well with the experimental result of a 10nm length change. It is also interesting to note that because the fiber end moves 10nm over 6ns, it accelerates at a rate of about  $10^8 m/s^2$ .

We have also measured fast hysteresis in an MPU on the nanosecond time scale. At this point, it is not clear whether the observation is due to a length change or a fast photobleaching process. Further study is required to resolve this issue.

### 3 Technology Transfer

One patent was issued and a second patent is pending. The technology at the heart of these patents has been transferred to Sentel Technologies. Sentel is in the process of commercializing this technology under an ARO STTR grant. NASA has funded Sentel to develop smart vibration sensors, which are a natural outgrowth of the ARO sponsored work.

### 4 List of Publications and Presentations

#### 4.1 Journal Articles

- D. J. Welker and M. G. Kuzyk, "Photomechanical Stabilization in a Polymer Fiber-Based All-Optical Circuit," *Appl. Phys. Lett.* **64**, 809 (1994).
- M. G. Kuzyk, D. J. Welker, and S. Zhou, "Photomechanical Effects in Polymer Optical Fiber," *Nonlinear Optics* **10**, 409 (1995).
- D. J. Welker and M. G. Kuzyk, "Optical and Mechanical Multistability in a Dye-Doped Polymer Fiber Fabry-Perot Waveguide," *Appl. Phys. Lett.* **66**, 2792 (1995).
- D. J. Welker and M. G. Kuzyk, "All-Optical Devices in Polymer Optical Fiber," *Nonlinear Optics* **15**, 435 (1996).
- D. J. Welker and M. G. Kuzyk, "All-Optical Switching in a Dye-Doped Polymer Fiber Fabry-Perot Waveguide," *Appl. Phys. Lett.* **69**, 1835 (1996).
- D. J. Welker and M. G. Kuzyk, "Stabilization of a sheet with an MPU," Submitted to *Opt. Lett.*

#### 4.2 Conference Articles (Proceedings)

- Mark G. Kuzyk, Q. Li, D. J. Welker, P. Young, S. Zhou, and C. W. Dirk, "New Device Concepts in Polymer Optical Fibers," Annual Meeting of the Optical Society of America, ACS/OSA Topical Meeting: Organic Thin Films for Photonic Applications (October, Toronto 1993) - **invited**.
- M. G. Kuzyk, Q. Li, D. J. Welker, S. Zhou, and C. W. Dirk "All-Optical and Photomechanical Devices in Polymer Optical Fiber," to appear in *SPIE Proc.* **2143**, EOLASE, Los Angeles 1994. - **invited**
- M. G. Kuzyk, D. J. Welker, and S. Zhou, "Photomechanical Stabilization and Positioning with Polymer Optical Fibers," *SPIE Symposium on Smart Structures and Materials*, *SPIE Proc.* **2189**, 249, Orlando (1994).
- D. J. Welker and M. G. Kuzyk, "Photomechanical Stabilization and Semi-Digital Positioning in a Polymer Fiber-Based All-Optical Circuit," *Proc. of the Second International Conference on Intelligent Materials*, 1308, Williamsburg, Technomic Press (1994).
- S. Zhou and M. G. Kuzyk, "Observation of Fast Photomechanical Effects in a Polymer Optical Fiber," *Proc. of the Second International Conference on Intelligent Materials*, 1375, Williamsburg, Technomic Press (1994).

- M. G. Kuzyk, Q. Li, M. Lobel, D. J. Welker, P. Young, S. Zhou, and C. W. Dirk, "Intensity-Induced Phase Shift Phenomena in Polymer Optical Fibers," Proc. 4th IKE-TANI Conference, 153 (1994). - **invited**
- S. Zhou and M. G. Kuzyk, "Fast Photomechanical Effects in a Polymer Optical Fiber," SPIE Proc. **2285**, 125 (1994).
- M. G. Kuzyk, "Third Order Optical Processes in Organic Materials," Proc. of QELS, Anaheim (1994). (invited)
- M. G. Kuzyk, T. M. Brown, Q. Li, C. Poga, D. J. Welker, P. Young, S. Zhou, and C. W. Dirk, "Photomechanical Phenomena in Polymer Optical Fibers," Proc. of the ACS/OSA Joint Topical Meeting: Organic Thin Films for Photonic Applications, Washington, DC (1994). Published in Polymer Preprints. - **invited**
- D. J. Welker and M. G. Kuzyk, "Photomechanical Multistability and Logic in a Polymer Optical Fiber," OSA 1995 Tech. Digest **21**, 313 (1995).
- D. J. Welker and M. G. Kuzyk, "All-Optical Devices in Polymer Optical Fiber," ICONO'2, 70 (1995).
- M. G. Kuzyk and D. J. Welker, "Mesoscopic Photomechanical Units and Ultrasmart Materials," SPIE Proc. **2441** (1995). - **invited**
- M. G. Kuzyk, S. Vigil, S. Zhou, D. J. Welker, "Ultrafast Multistability in Miniature Photomechanical Vibration Suppressors," SPIE Proc. **2716** (1996). - **invited**
- D. J. Welker and M. G. Kuzyk, "Smart Mesoscopic Photomechanical Positioner/Actuator, Sensor, and All-Optical Logic Unit," SPIE Proc. **2716** (1996). - **invited**
- D. J. Welker and M. G. Kuzyk, "All-Optical MPUs as Components of the Car of the Future," Proc. Int. Congress on Trans. Elec., Convergence'96, 493 (1996). - **invited**
- D. J. Welker and M. G. Kuzyk, "Vibration Suppression in a sheet with a Fabry-Perot Photomechanical Device," ICONO'3, Marco Island (1996).

#### 4.3 Book Chapters

- M. G. Kuzyk, "All-Optical Materials and Devices," in *Science and Technology of Organic Thin Films for Waveguiding Nonlinear Optics*, F. Kajzar and J. D. Swalen, eds., Gordon and Breach, New York (invited book chapter).
- M. G. Kuzyk, "Relationship between the molecular and bulk response," in *Linear and Nonlinear Optical Properties of Materials: Measurement Techniques and Tabulations*, M. G. Kuzyk and C. W. Dirk, eds., Marcel Dekker, New York (in press).

### 5 Scientific Personnel

Mark G. Kuzyk (PI); Graduate Students: Steve Vigil, David J. Welker, Shiliang Zhou; Undergraduate Students: Marc Dayton and Richard Welber; Technician: Phil Young. **Degree:** David J. Welker, M.S. Degree in Physics, awarded May 1994.

## 6 Inventions

### 6.1 Patents

- Patent # 5,446,808: "Photomechanical Positioning and Stabilization Method and Devices Using Optical Fibers and Feedback," M. G. Kuzyk and D. J. Welker, Patent Issued 8/29/95.
- "Miniaturized Photomechanical Vibration Suppressors," M. G. Kuzyk and D. J. Welker, Patent Application Submitted 1995.

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